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THE PYRAMIDAL TRACT IN THE CAT, DOG AND MONKEY.

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(Plates XIV., XV.)

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This paper[1] contains an account of the essential part of a research the results of which were embodied in a thesis[2] and presented for the degree of doctor of medicine of the University of Edinburgh in July 1901. The work was undertaken with a view to investigate the course pursued by the fibres of the pyramidal tract in their passage downwards through the brain and spinal cord, but more especially their mode of ending in relation to the cells of the cranial motor nuclei in the mesencephalon, pons and medulla oblongata, and of the grey matter in the spinal cord. Probably the pyramidal tract has been more carefully investigated than any other in the central nervous system, both experimentally in animals and clinico-pathologically in the human subject, but still the mode in which its fibres terminate, both in the lower regions of the brain and in the spinal cord, is a much disputed point, and some recent work seems to indicate that the view taken by most neurologists is probably not the correct one. The research, which extended over a period of two years, was carried out in the Physiological Laboratory of the University of Edinburgh under the direction of Professor Schäfer, and the expenses were defrayed by a grant from the Earl of Moray Research Fund. It consisted in establishing experimental lesions in the motor cortical centres in cats and monkeys, observing and recording the motor and sensory effects produced by such lesions, and in tracing the secondary degenerations resulting from them by the somewhat costly method of Marchi. By way of introduction I shall first give a short account of the work done by previous investigators, then state

[1] This paper, in a somewhat modified form, has already been published in the *International Monatschrift für Anat. und Physiol.*, Bd xix. Heft 7–9 (1902).

[2] The thesis was awarded a gold medal.

the methods adopted in the present research, and finally give the results obtained and compare them with those of former observers.

Part I.

Historical.—Prior to the year 1861, that is to say, until only about forty years ago, it was believed that the cortex of the cerebral hemispheres was not directly excitable by the application of a stimulus to it, and that there was no localisation of any particular function to any special part of the cerebrum. The cerebral hemispheres were supposed to act as a complete whole, and any voluntary movement or any change in the state of consciousness due to the incoming of any afferent impulse was believed to be effected by all parts of the cerebrum acting together. The chief exponent of this doctrine, as opposed to that of the school of Gall (1), was Flourens (2). He was warmly supported by Majendie and all the other eminent physiologists of the day, and even as late as 1876 Brown-Séquard (3) still held the same opinion.

In 1861 an important discovery in the localisation of function in the cerebral hemispheres was made by the French physician Broca (4) as the result of clinical and pathological observation. He noticed that when the posterior part of the left inferior frontal convolution was destroyed by the rupture of a blood-vessel or otherwise in a right-handed person, there was generally loss of the power of speech, or rather loss of the power of remembering words required for speech. This is the first distinct evidence we have of cerebral localisation. Shortly thereafter the Flourens doctrine was again challenged by Hughlings Jackson (5) of London. He observed that in certain cases of epilepsy he could trace the cause to some injury of the skull or cerebral cortex. In such cases the convulsive movements began in some particular part and spread from that part, *e.g.* began in the fingers and spread up the arm, the movements following a certain order or "march." From these clinical and pathological observations Jackson reasoned that the irritation produced by the injury or disease of the cerebral cortex in the region now known as the Rolandic area was the cause of the convulsive movements

or "fit." This is the first idea we get of motor localisation. With Jackson at that time it was only a hypothesis, but since then this has been abundantly proved to be correct.

In 1870 Fritsch and Hitzig (6) showed that stimulation by galvanic electricity of certain parts of the cerebral convolutions surrounding the crucial sulcus in the brain of the dog led to certain definite movements of the limbs on the opposite side of the body, stimulation of the same part of the cortex always producing the same movement of the limb. They also found that extirpation of these particular parts of the cortex led to paralysis of the same muscles as were excited by stimulation. Stimulation of other parts of the cortex could not be made to produce these movements. This is the first direct proof we have of a cerebral cortical motor area. In 1873 Ferrier (7), using faradic electricity as a stimulus, repeated the experiments of Fritsch and Hitzig on cats, dogs and monkeys. He confirmed their observations and greatly extended them. He was able to localise and map out, especially in the monkey, those areas which on stimulation produced movements of the face, arm, trunk and leg of the opposite side of the body. He added many new facts regarding motor centres, and he was the first to discover sensory centres. These general results of Ferrier's experiments were subsequently much amplified by Horsley and Schäfer (8), and later by Beevor and Horsley (9); and now, as regards the brain of the monkey, our knowledge of these cortical motor areas may be considered to be very nearly complete, but still, in view of the recent experiments of Grünbaum and Sherrington, a more precise delimitation of these areas may yet be possible.

The cortex of the orang-utang was explored by Beevor and Horsley (10), and they found that while the excitable areas for the most part corresponded with those in the macaque monkey, yet there was one marked difference, viz., that the excitable region was not continuous as in the monkey, but was interrupted by small areas, stimulation of which produced no movement of any muscle. Their observations, however, are not supported by those of Grünbaum and Sherrington (11). These latter investigators experimented on the orang, the gorilla and the chimpanzee, using the unipolar method of stimulation, and they found the motor area to be much less extensive than it had hitherto been

supposed to be. It included continuously the whole length of the precentral or ascending frontal convolution, but did not extend at any point behind the fissure of Rolando, so that this fissure would seem to mark a physiological as well as an anatomical division of the brain. On the mesial surface of the hemisphere also the motor area was found to extend downwards for a shorter distance than was expected,—it did not reach the calloso-marginal fissure.

In a few cases also, chiefly in America (12, 13, 14, 15, 16), the human brain has been proved to be directly excitable by electrical stimulation. In these cases the areas under observation were necessarily limited, but in the main they have been found to correspond with those mapped out on the brain of the monkey.

We must next consider the path pursued by the fibres which carry the impulses from the cells situated in the motor cortex to the cells of origin of the cranial motor nerves and of the anterior spinal nerve roots, that is to say, the fibres which together make up the pyramidal tract. Several methods have been employed for investigating the course of these fibres, but the two most important may be said to be the *embryological method of Flechsig* and the *Wallerian method or method of secondary degeneration.* As the latter has been used exclusively in the present research, it may be well to review briefly the work done by previous observers and the results they have obtained by this method.

The Degeneration Method was first in the field, and has probably been more fruitful than any other in advancing our knowledge of this subject. It depends upon the fact, first discovered by Dr Waller (17) of London about the year 1850, that when a nerve fibre is cut off from that part of its cell of origin containing the nucleus, it undergoes degeneration. Any lesion in the brain or spinal cord which so cuts off a fibre or tract of fibres leads to a degeneration of that fibre or tract of fibres,—descending if the cell be above the lesion, ascending if the cell be below it. Such a lesion may be produced experimentally on one of the lower animals anæsthetised, or it may occur in the human subject as the result of accident or disease. By certain methods of staining, which will be given in detail subsequently,

it is easy to distinguish degenerated parts in sections of the brain or spinal cord, if the production of the lesion is followed by death within certain limits of time.

The earliest observer to study the minute anatomy of the brain by the method of degeneration was Cruveilhier (18) in 1835, but he did not understand the principle on which the changes that he observed depended. It was Türck (19), in 1851, who gave us the first complete account of the descending tracts. In certain long-standing cases of hemiplegia, he observed in transverse sections of the pons, bulb and spinal cord certain areas which, as he termed it, had become "secondarily diseased." He was able in this way to locate the motor path approximately in the internal capsule, crusta, pyramidal bundles of pons, and anterior pyramids of medulla oblongata. He also made out the pyramidal decussation in the lower part of the bulb, and in addition to the crossed tract in the spinal cord he observed a direct or uncrossed tract lying close to the anterior median fissure. This tract was subsequently named by Charcot "the column of Türck."

The next in the field was Bouchard (20) in 1866. In a series of articles published in the *Archives Général de Médicine* of that year he gives the results of his observations of secondary degeneration following lesions in the cerebral hemispheres, cerebral peduncles, pons, bulb, spinal cord and posterior nerve roots in the human subject, produced by tumour, hæmorrhage or compression. He was able to make out in the main the descending (motor) tracts as we now know them. He found that, following lesions of the encephalon, the descending degeneration was not scattered over the whole extent of the antero-lateral columns of the cord. He also found that most of the fibres which the brain sends to the spinal cord cross the middle line at the lower part of the bulb, to take up a position in the posterior part of the lateral column of the opposite side in the cord, a position which they retain throughout the whole length of their course. They gradually ended in the grey matter of the cord, and became fewer and fewer from above downwards, but some could be followed to "*l'extrémité inférieure de l'axe rachidien.*" This tract he called the "*faisceau encéphalique croisé ou externe.*" He further found that the crossing of the

pyramids was not complete; some fibres passed down along the side of the anterior median fissure, gradually becoming lost in the grey matter of the cord, and could not be traced below the middle of the dorsal region. This he called the "*faisceau encéphalique direct ou interne.*" The degeneration did not extend into the roots of the spinal nerves, and from this he concluded that the degenerated fibres ended in the grey matter of the spinal cord. He recognised the great importance of this method of secondary degeneration which Waller had applied to the study of the peripheral nerves, as a means of investigating the minute anatomy of the brain and spinal cord.

Following this important communication, valuable work on the same lines was done by Charcot (21), Pierret (22) (who investigated the ascending degeneration resulting from lesions of the posterior nerve roots), and Nothnagel (23), which may be passed over, as they merely confirmed the observations of Türck and Bouchard.

We now come to a new departure in the mode of investigation, which consists in simulating artificially in animals the lesions produced by disease or accident in man. In 1877 and 1878 Franck and Pitres (24) removed the cortical centre for the left fore-limb in one dog, and the whole of the right sigmoid gyrus in another. The one died nine months and the other was killed six months after the operation. Motor paralysis of the opposite side resulted, and along with this there was some sensory disturbance, but both were quickly recovered from, and in neither case was there any contracture of the paralysed limbs, as had so often been observed in cases of hemiplegia in man. In both instances they found degeneration in the lateral columns of the spinal cord of the opposite side, but from their paper it may be gathered that the secondary degeneration in these two cases might have been, in their opinion, accidental, and that it was not always a necessary result of cortical ablation.

In 1882 Moeli and Binswanger (25), and later Moeli (26) working alone, found that after injury to or removal of the cerebral motor cortex in the dog, descending secondary degeneration always followed. The animals had been operated on by Munk, and they showed partial motor and complete sensory paralysis of the opposite side. Binswanger (27), who had done

similar experiments previously, had denied that this was the case, but he now corrected this statement, and gave as the reason of his failure, that he had allowed the animals to live too long after the lesion had been produced. Moeli and Binswanger often found evidence of secondary degeneration in the brain and spinal cord in animals in which there had been no evidence of motor paralysis during life.

In 1883 Schäfer (28) was given for microscopical examination, the brain and part of the spinal cord of a monkey which some months previously had had "the whole of the centre of the fronto-parietal region on the left side of the cerebrum" removed by Ferrier and Yeo. There was no injury to the corpus striatum or optic thalamus; it was a purely cortical lesion. He found degeneration in the internal capsule, middle portion of crusta, pons and medulla oblongata—all on the side of the lesion. In the lower part of the bulb in the region of the pyramidal decussation he found that "the degenerated tract passes obliquely across the anterior median fissure to the opposite or right side of the medulla. Here it runs down for a short distance in the formatio reticularis. A portion of the tract remains, however, at first in the anterior column, and this portion, or at least a considerable part of it, at a little lower level, appears to be passing towards the formatio reticularis of the same or left side of the medulla." In the cervical part of the cord the crossed pyramidal tract of the right (opposite) side was degenerated, as was to be expected, "but what was not to have been expected is the presence of another patch of degeneration upon the left side of the cord (side of injury), occupying almost exactly the same position and of the same extent as the degeneration on the right side, but less accentuated by the process of staining employed, and therefore probably containing fewer degenerated fibres. The degeneration in the cervical cord is therefore bilateral." The sections from the dorsal and lumbar regions of the cord were prepared and examined by Ferrier, and in these there was no evidence of any degeneration on the same side as the lesion—it was limited entirely to the crossed pyramidal tract of the opposite side. This is the first recorded observation of a two-sided lateral column degeneration in the spinal cord following a unilateral cortical lesion in the cerebrum,

and the explanation offered at that time by Schäfer as the probable one has since been proved to be correct. He says—"The only gleam of elucidation as to the source of the degenerated fibres in the left lateral column in this (cervical) region which it has been possible to obtain is to be found in the observation above recorded of the apparent passage of a small part of the degenerated left anterior pyramid towards the left lateral column, whilst the larger part took the more usual course towards the opposite lateral column. I have searched in vain for any sign of degeneration along the pyramidal tract of the right side of the medulla, pons and crus cerebri, and of the right internal capsule."

Shortly after this, in 1884, Pitres (29) published the results of his examination of forty cases of long-standing hemiplegia, and in ten out of these forty cases he found descending degeneration in the lateral columns of both sides of the cord. In summing up he says, "No author, so far as I know, has as yet described symmetrical degeneration of the lateral columns of the spinal cord following unilateral cerebral lesions." This was true only of the human subject, for Schäfer had described it in the monkey in 1883.

The explanation of this bilateral pyramidal degeneration in the lateral columns of the spinal cord, as the result of damage to one side of the cerebrum, was for a long time a source of fruitful discussion. Clinical evidence of a bilateral motor distribution from one side of the brain was known long before the observations of Schäfer and Pitres. Brown-Séquard long ago pointed out that in cases of hemiplegia the so-called sound side is never so strong as it was before the attack,—that there is always a certain amount of weakness in the non-paralysed side, as well as marked weakness or complete loss of power in the paralysed side. The author has been told by Professor Greenfield that Hughlings Jackson taught this at his cliniques in the early sixties. In 1875 Westphal (30) remarked that in certain cases of hemiplegia with contracture, the so-called sound lower limb showed ankle clonus. In 1878 Dejerine (31) observed the same phenomenon,—ankle clonus in the so-called sound lower limb, and to explain it he put forward the hypothesis that it was due to a descending sclerosis of the pyramidal bundle of the

sound side. In 1880 Brissaud (32) described contracture in both lower limbs which he had sometimes found in hemiplegias. In 1880, and again in 1882 Pitres (33) studied these bilateral symptoms clinically, and often found evidence of some paralysis on the sound side in cases where the post-mortem examination showed the lesion to be strictly confined to one side of the cerebrum. He stated that in some cases the so-called sound upper limb loses as much as 38·5 per cent. of its original power, and the lower limb as much as 50 per cent. In 1883 Dignat (34), and in the same year Friedländer (35), made more accurate observations with the dynamometer, and both found that there was always a considerable loss of power on the non-paralysed side.

Charcot (36) attempted to explain the partial paralysis of the sound side on an anatomical hypothesis, which would also account for the descending bilateral degeneration in the spinal cord. He held as possible that some of the fibres from the crossed pyramidal tract "pass through the anterior commissure, especially in the dorsal region, and gain the lateral column of the opposite side, to descend with it into the lumbar region. There exists, then, for these fibres a double decussation,—one in the bulb (anterior pyramidal decussation), and the other at different points throughout the whole dorsal region of the cord."

Following Schäfer in the monkey and Pitres in man, Langley and Sherrington (37) in 1884 found in a dog, from which Goltz had removed a large area of the cerebral cortex, and which was exhibited by him at the International Medical Congress held in London in 1881, sclerosis in the lateral pyramidal tract on each side of the cord, which they were able to trace as far as the lumbar region. They found only unilateral degeneration above the pyramidal decussation.

Again, in 1885, Loewenthal (38) found in the dog bilateral cord degeneration after unilateral cortical lesions.

In the same year (1885) Sherrington (39) began an elaborate research into the nature and origin of this bilateral degeneration in the spinal cord, which was now considered to be an established fact. His first observations were made on material obtained from dogs which had been operated on by Goltz. He found "1. That injury to the 'cord-area' of the cortex of one hemisphere

causes degeneration in both halves of the spinal cord in the dorsal angle of the lateral column, and that there is no reason to think this bilateral degeneration is a degeneration of the two crossed pyramidal tracts. 2. That the clinical symptoms of a unilateral cortex injury become bilateral, and accord with the bilateral anatomical change." The degeneration in the cord on the same side as the cortical lesion did not seem to be so far advanced as that on the opposite side, and this he supposed to be due to the fact that the degeneration on the same side was of more recent date. This tract on the same side he called the "re-crossed" tract, supposing that its constituent fibres crossed over in the cord from the opposite degenerated pyramidal tract. These fibres, he believed, crossed the middle line twice—once in the pyramidal decussation, and a second time back again to the same side in the cord. He did not think that this recrossed tract represented in any way the direct pyramidal tract in man. Both crossed and recrossed tracts he was able to trace as far as the second lumbar nerve root. This view of Sherrington with regard to the recrossing of some of the pyramidal fibres in the spinal cord seems to be identical with that of Charcot already given.

Regarding the recrossing of the fibres in the cord, Sherrington was supported by Homen and others. Homen (40) in the same year (1885), after hemisecting the cord in dogs in the cervical region, found some degenerated fibres in the crossed pyramidal tract of the opposite side, and these fibres, he concluded, must cross in the cord. He also stated that he found degeneration of the direct pyramidal tract in the dog, but here he was certainly in error, what he saw being evidently a portion of the descending antero-lateral tract of Loewenthal.

Others again denied the existence of the "recrossed" tract of Sherrington, and denied even the existence of a bilateral degeneration in the cord. For example, Ziehen (41) in 1887 extirpated the motor areas on one side in three dogs, and found in the spinal cord the degeneration limited to the crossed pyramidal tract of the opposite side but no degeneration on the same side as the lesion. Mott (42) likewise, in 1891, after hemisection of the cord in monkeys, denied any evidence in favour of a re-crossing of pyramidal fibres in the cord.

In 1889 Tooth (43), examining material obtained from monkeys from which Horsley had removed partially or completely the motor cortex on one side, found in the cord very obvious degeneration of the crossed pyramidal tract of the opposite side, but only a very slight degeneration of that of the same side.

In a case of right-sided hemiplegia, due to hemorrhage in the left internal capsule in the human subject, Hadden and Sherrington (44) in 1886 found the left anterior pyramid degenerated and the right very slightly so. They observed a great diminution in the number of degenerated fibres in the region of the pyramidal decussation as the tract passes from one side of the bulb to the opposite side of the cord, and they found a doubly bilateral degeneration in the spinal cord—a degeneration of both crossed and both direct pyramidal tracts. It seemed difficult to explain this as the result of a unilateral lesion unless the view of Hamilton were correct, viz., that the fibres from the cortex of one hemisphere cross in the corpus callosum and descend through the opposite internal capsule. In a paper published in 1884, Hamilton (45) made the statement that "the corpus callosum is not an inter-hemispheric commissure at all, but is the decussation of the cortical fibres in their progress downwards to become connected with the basal ganglia. In the human brain I have never seen any fibres which pass directly from one hemisphere to another." This view was strongly opposed by Beevor (46) and others at that time, and since then it has been abundantly proved to be quite erroneous.

In 1889 Franee (47) published a paper giving the results of an investigation into the degenerations following removal of the gyrus fornicatus and gyrus marginalis in six monkeys (used in the localisation experiments of Horsley and Schäfer), and also following removal of the external motor cortex (three cases), and of the whole motor cortex (external and mesial) in four cases. After removal of the external motor cortex he found degeneration in the middle third of the inner capsule. It did not, however, involve the whole breadth of the capsule, but left the inner border almost entirely free. This inner border was occupied by fibres from the marginal convolution, "as is proved by the fact that when the entire motor area (including the gyrus

marginalis) is removed, the whole width of the internal capsule is degenerated." In the crusta the degeneration occupied the middle third both after removal of the whole and of the external motor cortex alone, but in the latter case it was greater along the ventral than along the dorsal border. "In the medulla the whole area of the pyramid is degenerated in those cases where the whole motor area was removed, whilst in those where only the external motor area was involved a part along the posterior mesial border appears less degenerated than the rest." Throughout the spinal cord the crossed pyramidal tract of the opposite side was degenerated down to the level of the third or fourth lumbar nerve. The fibres from the marginal convolution were found to border on the direct cerebellar tract. According to his results, the fibres from the marginal convolution occupy more or less the inner border of the internal capsule (next the optic thalamus), the anterior portion of the crusta, the postero-mesial border of the anterior pyramid, and in the cervical cord that portion of the crossed pyramidal tract lying next the direct cerebellar tract. In the dorsal and lumbar regions of the cord the position of the degenerated fibres from the marginal convolution within the area of the crossed pyramidal tract could not be localised. No mention is made of any degeneration in the crossed pyramidal tract of the same side. In no case was any degeneration observed in the anterior columns.

In 1889 Sherrington (48) experimented on dogs and monkeys with the object of finding out "to what extent in the pyramidal tract there is a grouping of nerve fibres, corresponding to the grouping of nerve cells in the 'cord-area' of the cerebral cortex." By 'cord-area' of cortex he meant that area, injuries to which, are followed by degeneration of nerve fibres in the spinal cord. He found no grouping of the arm or leg fibres in the cord. After very small cortical lesions within the arm and leg centres, degenerated fibres were found scattered over the whole transverse area of the tract in the spinal cord, medulla, pons and crusta of mid-brain. In every case a unilateral cortical lesion or hemisection of the spinal cord was followed by degeneration in the pyramidal tract below in both lateral columns of the cord. Counting the degenerated fibres, the amount of degeneration on the same side varied in different

cases from $\frac{1}{100}$ to $\frac{1}{5}$ of that on the opposite side. In one dog he saw slight degeneration of the opposite pyramid above the decussation. From the degenerations the following points were made out for the "re-crossed" tracts:—"1. They consist of fibres derived from the crossed tract of the opposite half of the cord, and are directly connected (*i.e.* without the intermediation of nerve-cells) with that cortex which is the place of origin of the crossed tract whence they come. 2. Their path of connection twice crossed the middle line, the proximal crossing being at the pyramidal decussation. . . . 4. They occupy the same area in a transverse section of the cord as does the crossed pyramidal tract amongst the fibres of the crossed tract from the left hemisphere being scattered those of the re-crossed tract from the right hemisphere. Insistence may be laid upon the pyramidal tract as a line of *direct* communication of each hemisphere of the brain with *both* halves of the spinal cord, and not with one only as generally described." He also found that the fibres of both the crossed and the "re-crossed" tracts diminish most rapidly in number in the lower parts of the cervical and lumbar enlargements after lesions of the arm and leg areas respectively, and in face area lesions the diminution takes place most rapidly in the pyramid just below the pons, and he infers from this that the fibres which are lost end in grey matter in these regions.

Shortly after this, in an addendum to the last communication, Sherrington (49) withdrew the term "re-crossed fibres." He had now found bilateral degeneration in the pyramidal tracts at the base of the brain in monkeys, as he had once before in the dog and once in man (already mentioned), but he does not state exactly where he supposes the degenerated fibres are derived from, or at what point they cross the middle line, nor does he say whether he supports Hamilton in the view that the fibres cross in the corpus callosum.

Still continuing his researches on this subject in a paper published in 1890, Sherrington (50) states that when following a cortical lesion the pyramidal tract degenerates, scattered fibres are found undergoing degeneration in the anterior grey horn of the spinal cord, lateral grey horn, "isolated grey masses in the pons," and in the substantia nigra in the mid-brain. These fibres in the grey matter were always of smaller size than those

of the pyramidal tract, and this he supposes to be due to the subdivision of the pyramidal fibres before entering the grey matter. In cortical lesions confined to the leg area, he still found many degenerated fibres in the substantia nigra of the crus.

In 1890 Langley and Grünbaum (51) investigated the degeneration following the removal of one cerebral hemisphere in a dog operated on by Goltz, and exhibited by him at the Physiological Congress at Basle in 1889. They describe complete degeneration of the pyramid, atrophy of the substantia nigra, tegmentum, and grey matter of aqueduct on the same side as the lesion. There was a unilateral degeneration in the crusta, pons and medulla oblongata, and bilateral degeneration in the cord, and in the crossed pyramidal tract of the same side the degeneration was very slight.

Marchi's Method.—The study of degeneration had up till this time been carried out by simply staining the sections with carmine or blue-black, or by Weigert's method, or Pal's modification of that method, but since about 1891 the much more accurate and delicate method of Marchi has been employed by almost all investigators, and the introduction of this method in 1887 marks an epoch in the history of the study of degeneration in the central nervous system, as had that of Golgi in relation to the structure of the grey matter. By this method it has been possible to trace the distribution of the pyramidal fibres, and even of their collaterals, with far greater exactness than was possible with the older methods, and consequently the results are much more valuable. Of course in only a limited number of cases in the human subject is it possible to employ the Marchi method,—only in cases which terminate fatally not earlier than about seven days and not later than two or three months after the occurrence of the lesion which has led to the degeneration. If it be of longer duration, then the Weigert-Pal method must be had recourse to. For some time after its introduction it was regarded by many eminent neurologists as quite unreliable, but the errors made by Marchi in his earliest applications of the method were largely responsible for this.

One of the earliest to use this method in tracing motor degeneration was Sandmeyer (52) in 1891. He removed the arm, leg and face cortical centres in dogs on one side. Thirteen

animals were used, and in seven of these the degenerations were investigated by the Marchi method. He found the usual unilateral degeneration in the medulla oblongata and pons, and he sometimes found a bilateral degeneration in the lateral columns of the spinal cord, but not always. In no case did he find a direct pyramidal tract in the dog. He makes no mention of having traced any of the degenerated pyramidal fibres to their termination in the grey matter, either in the cord or brain.

Max Herz (53), at a meeting of the "Geselschaft der Aertze in Wien" on Feb. 27th, 1892, exhibited microscopical preparations of sections of the spinal cord of a monkey which died five months after the right motor cortex was removed. These showed degeneration in both pyramidal tracts, but much less in the uncrossed than in the crossed tract. He employed the Weigert-Pal method of staining, as he was precluded from using the Marchi method by the age of the degeneration.

In 1893 Muratoff (54) used dogs which were killed from two to four weeks after the production of experimental lesions. The material was prepared by Marchi's method. After stimulating to localise, he extirpated the arm, leg, face, or whole motor area, as the case might be. He found the usual unilateral degeneration on the side of the lesion in the crusta, pons and medulla oblongata. From the crusta he deseribes degenerated fibres passing backwards into the tegmentum towards the anterior corpus quadrigeminum. In the cases in which the face centre alone was extirpated, he deseribes at the level of the 7th nucleus degenerated fibres running backwards from the inner and posterior angle of the pyramid, and after crossing the raphe, passing in the direction of the nucleus of the facial nerve. In cases in which the arm and leg areas respectively had been removed alone, no such fibres were to be seen. He observed degenerated fibres in both lateral columns of the spinal cord, and he described the passage of some degenerated fibres at the decussation into the crossed pyramidal tract of the same side as the lesion. Risien Russel (55) claims to have been the first to observe the bifurcation of the pyramidal tract at the decussation in a cat in which there had been an arrest of development of the pyramidal tract on one side, but Muratoff's observations were placed on record prior to the publication of Russel's paper.

In this animal (Russel's) about one-fifth of the fibres were uncrossed at the decussation, and could be seen passing backwards and outwards to take up a position in the crossed pyramidal tract of the same side in the cord.

In 1894 Sherrington (56), again taking up this subject, removed a small piece of the cortex from the left arm area of four monkeys, and killed them from fourteen to twenty-eight days after the operation. He confirmed the observation of Muratoff as to the bifurcation of the pyramidal tract at the decussation. In one of the experiments he found as many as one-fourth of the degenerated fibres uncrossed in the lateral column of the same side of the cord.

Mellus (57), in 1894, under the direction of Horsley, produced experimental lesions in fourteen bonnet monkeys. He removed small areas from the left motor cortex; in three cases he removed the hallux centre, in four cases the thumb centre, and in seven cases different centres within the facial area. The animals were killed from ten to thirty-five days after the lesions were made, and the brain and cord in each case prepared by the process of Marchi. He attempted to trace the commissural, association and projection fibres which had degenerated as the result of the lesions. We shall confine our attention exclusively to the projection fibres. In every instance coarse and fine fibres were found. In the case of the *hallux centre* the degenerated fibres passed through the mesial part of the centrum ovale to the middle third of the internal capsule, and from there most of the fine fibres passed into the optic thalamus. In the crus the degenerated fibres were comparatively evenly scattered over the middle third. At this level many of the coarser fibres entered the substantia nigra. At the pyramidal decussation the degenerated fibres divided into three parts,—most crossed to descend in the lateral column of the opposite side of the cord (crossed pyramidal tract), a smaller number passed into the lateral column of the cord on the same side (from one-third to one-tenth of the whole in the different cases), and a few passed down the anterior column of the cord on the same side (direct pyramidal tract). There was no apparent localisation of the degenerated fibres to any particular part of the tract; they were scattered evenly over the whole area of the cross section on both

sides. Degenerated fibres in all three tracts were found as low as the level of the third sacral nerve root. From the *thumb centre*, most of the fine fibres ended in the optic thalamus. In one or two cases he found fine fibres in the right internal capsule on the side opposite to the lesion; these ended in the right thalmus, and *came from the thumb centre on the right side* and not from the corpus callosum! In the crusta, again, the degeneration was scattered evenly over the middle third; the fine fibres took up a position external to the coarse, and a great number of both passed into the substantia nigra. On the right side, in one or two cases, degenerated fibres reached the crus from the right internal capsule, and ended at that level in the substantia nigra. Many of the fibres on the left side were lost in the pons and medulla oblongata, but their ultimate distribution could not be traced. In three cases the decussation at the lower end of the bulb was complete, and in only one (out of four) was there fibres traced to the uncrossed lateral and direct anterior pyramidal tracts of the same side. The fibres began to disappear at the level of the 7th cervical root, and had all vanished at the level of the 3rd dorsal root. From the *facial area* degenerated fibres were again traced into the internal capsule, gradually passing from before backwards in the different levels of the capsule from above downwards. Most of the fine degeneration here also passed into the optic thalamus, but this was not so in every case. In several of the cases there was degeneration in the internal capsule of the right side, traceable again to the corresponding areas in the motor cortex of the same (right) side. From the crusta many of the fibres passed to the substantia nigra, "and the remaining degenerate fibres begin to leave the left pyramid at the junction of the pons and medulla, passing as single degenerate fibres to the facial nucleus of one or the other side. Below the level of the facial nucleus, these fibres pass to the motor nuclei of the glosso-pharyngeus and vagus on both sides, the majority crossing the raphe to reach the nucleus of the opposite side. Occasional fibres were observed which apparently passed to some termination dorsal to these nuclei. This movement of degenerated fibres continued as far as the sensory decussation." Here Mellus states that he was able to trace fibres from the pyramidal

tract passing to the cranial motor nuclei of both sides—most to the nuclei of the opposite side, a few to those of the same side.

In the same year (1894) Boyce (58), in the course of a very extensive research, removed in the case of four cats the whole motor area on one side, and traced by the Marchi method the resulting degenerations. He found degenerated fibres from the internal capsule passing into the optic thalamus and some ending in the lateral geniculate body. There was uniform degeneration in the crusta—not limited to any one particular part of it. He found no degenerated fibres in the opposite internal capsule, and on this point he does not confirm the results of Mellus in the monkey. The degenerated pyramidal tract was seen to divide into two parts at the decussation, most crossing to the lateral column of the opposite side of the cord, and very few passing to the same side. No direct pyramidal tract was observed in the cat. He agrees with Muratoff and Mellus that a few fibres in the upper part of the medulla oblongata leave the pyramid at its inner and posterior angle, but he has never been able to trace these or any other fibres coming from the degenerated pyramid to any of the cranial nerve nuclei. In two cases he found a few fibres passing from the outer and upper extremity of the degenerated crusta to the anterior corpus quadrigeminum of the same side.

In 1896 Dejerine and Thomas (59) published results of seven cases in the human subject of total degeneration of the pyramid following unilateral hemispherical lesions. They showed in all these cases a degeneration of the direct pyramidal tract in the anterior column of the cord on the same side as the cerebral or pontal lesion, a degeneration of the crossed pyramidal tract of the side opposite to the lesion, and a slight degeneration in the crossed pyramidal tract on the same side as the lesion. In two of the cases, one of which was recent, and suitable for Marchi staining, they were able to trace the passage of degenerated fibres at the decussation to both lateral columns of the cord, while some remained in the anterior column of the same side. The fibres which passed to the lateral column of the same side these authors termed "homolateral pyramidal fibres," while those going to the opposite side they termed "heterolateral fibres."

They traced the crossed pyramidal tract to the level of the upper end of the filum terminale, the direct anterior and lateral tracts being found as low as the level of the fourth sacral root,—farther than any of these tracts had been followed before. They found no degeneration in the anterior pyramid of the opposite side above the decussation.

In 1896 Rothmann (60), working in Munk's laboratory, examined the brains and spinal cords of eleven dogs and two monkeys in which the fore and hind limb areas had been extirpated by Munk on one side. In some cases he used the Marchi method and in others the method of Weigert. In every case he observed a bilateral crossed pyramidal tract degeneration in the cord up to four weeks after the lesion. It was much less abundant on the same side than on the opposite side, but still it was quite evident. In the course of from two to four months the degeneration on the same side had disappeared. The degeneration on the same side began at the decussation, and he came to the conclusion that it was due to pressure at the crossing of the swollen bundles of the degenerating pyramid on some of the fibres of the normal pyramid. He says that a crossing within the cord does not exist. Taking up this matter quite recently, however, Rothmann (61) has come to a different conclusion. Munk removed the leg and arm centres on the left side in a monkey, allowed the animal to live four months, and thirteen days before killing it he made a similar lesion on the right side. Rothmann prepared the cord and medulla oblongata by the Marchi method, and he was able readily to distinguish the old from the new degeneration by the fact that in the case of the old the course of the fibres was marked by fine black points, whereas in the new the degenerated stained myelin was disposed more or less in the form of continuous black lines. In the upper and lower parts of the decussation the crossing of the fibres was complete, but in the middle portion some fibres from the right pyramid (recent degeneration) were observed going to the right crossed pyramidal tract. These could not be due to pressure from the bundles of the left pyramid, as that pyramid had undergone degeneration long before. Rothmann doubts no longer the existence of fibres passing from each pyramid in the medulla to the crossed pyramidal tract of the same side, but he

still holds to the opinion that pressure at the crossing accounts for some of the homolateral degeneration.

Redlich (62) in 1897 investigated the course and termination of the pyramidal fibres in the brain and cords in cats. In four cases he extirpated the motor region of the left cerebral hemisphere, and in one the motor region on both sides. He used the method of Marchi, having previously hardened the tissue in a mixture of Müller's fluid and 2 per cent. formalin. His results agree for the most part with those of previous observers. In sections through the upper parts of the mid-brain there was much degeneration scattered throughout the crusta except at the lateral margin, which was free from degeneration. In sections at a lower level this non-degenerated area was seen to extend more towards the middle line along the anterior border of the crusta, so that the degenerated area was bounded antero-laterally by the non-degenerated area. In the pons and medulla this non-degenerated area had disappeared, and all the pyramidal bundles were thickly studded with degenerated fibres. At the decussation some fibres could be traced passing from the degenerated pyramid to the crossed pyramidal tract of the same side. He says that Rothmann is probably in error in supposing this to be due to pressure. These homolateral fibres could be traced to the lower end of the thoracic region. He supports Monakow in supposing that the fibres of the pyramidal tract do not end directly in relation to the cells of the anterior cornua of the spinal cord.

Hoche (63) in 1898 was able to apply the Marchi method to the study of the degenerations following unilateral motor lesions in two fatal cases of hemiplegia. He found degeneration in the middle portions of the crusta only, the most mesial and lateral portions being free. The degenerated fibres situated most laterally in the crusta became a separate bundle in the pons, which could be traced down through the median fillet in the pons and upper part of medulla oblongata. Fibres from this bundle were seen to pass to the nuclei of the 7th and 12th cranial nerves on both sides, most crossing the median raphe to the nuclei of the opposite side. He was also able to trace fibres from the degenerated pyramid to these same nuclei on both sides, showing that there are two distinct paths through which the 7th and 12th nerves may be thrown under the influence of the motor

cortex. In the cord he states that he was able to trace degenerated fibres from both lateral pyramidal tracts into the grey matter of the anterior horns, and from the direct pyramidal tract also he could trace fibres passing into the anterior horns of both sides, but mainly of the opposite side.

Dejerine and Long (64) in 1898 recorded five cases of cerebral hemiplegia, some right, some left; and as the age of the lesions ranged from twenty days to two months, all were suitable for the method of Marchi. The results of their examination of the brain and cord they summarise somewhat as follows:—The substantia nigra receives from the crusta numerous fibres which arborise round its cellular groups. The lateral fillet (fillet of Reil) receives deep and superficial fibres from the crusta, and also some fibres from the pyramidal tract as it passes through the pons, and these three sets of fibres rejoin the pyramid in the medulla. These they call aberrant peduncular and aberrant pontine fibres. They go on to say that "Contrary to what has been stated by Hoche, we have not been able to trace any degenerated fibres to any of the motor nuclei of the cranial nerves," and "we have obtained the same negative results for the degenerated pyramidal fibres in the spinal cord, which we have never been able to follow to the cells of the anterior horns . . . ." "In the grey substance of the pons the very fine and very numerous granules which we have observed in two of the cases indicate a degeneration of collateral and terminal fibres at this level, and this fact explains to us the atrophy of the grey substance of the pons which one sees in old degenerations of the crus cerebri."

Romanow (65) in 1898 experimented on dogs. He localised the cortical centres of the cranial motor nerves, and then ablated the particular centre with a sharp spoon. After from twenty to thirty days the animals were killed, and the medulla and pons stained by Marchi's method. He traced the degenerated fibres down through the internal capsule, crusta, pons and medulla to the level of each of the nuclei, and at these levels he states that degenerated fibres could be seen passing backwards and crossing the middle line to the other side. In each case the fibres in question began to leave the pyramidal tract a little above the level of the nucleus to which they were destined (5th, 7th or 12th), and continued to pass off until a little above the level of

the lower end of the nucleus. In the case of ablation of the cortical centre for the 7th nucleus degenerated fibres were traced close to the nucleus, but in the cases of the 5th and 12th they could not be traced quite up to the nuclei. In the 5th and 7th degenerated fibres could also be traced going to the nuclei of the same side.

Spiller (66) in 1899 described in the human subject a bundle of degenerated fibres which became detached from the extreme lateral part of the pyramidal tract a little below the level of the origin of the 5th nerve in the pons and passed downwards through the lower part of the pons and medulla oblongata as a separate fasciculus. At the junction of the pons and medulla this tract was found lateral to the uppermost part of the inferior olive; the thickening of the olive pushed the tract backwards, and at a lower level it lay close to and on the postero-lateral aspect of the olive. Below the pyramidal decussation the bundle lay on the same side as the lesion (which was due to a hæmorrhage in the external capsule and lenticular nucleus, damaging, of course, the internal capsule as well), that is to say, it remained uncrossed, and could not be followed farther than the first cervical segment, because the spinal cord had not been preserved. The bundle consisted of "numerous degenerated fibres." In an article which appeared recently (1902) in the *Neurologisches Centralblatt* he comes to the conclusion that this bundle becomes in the spinal cord a direct pyramidal tract in the ventro-lateral column, thus giving, he says, a direct pyramidal tract, a direct ventro-lateral pyramidal tract, and a crossed pyramidal tract. These three tracts in the spinal cord, it must be remembered, were described by Pitres in the human subject as early as 1884, and the direct ventro-lateral pyramidal tract in the monkey was described by Schäfer in 1883, and both these observations have been confirmed many times since then, but the fibres of the direct lateral tract were supposed to leave the degenerated pyramid entirely at the decussation, and not above that level, as Spiller has shown that they may do.

In 1898 (the work was published in 1901) Mellus (67) excised the left thumb centre in a bonnet monkey, and examined the resulting degenerations by the Marchi method. He says, "the feature of special interest in this group of experiments (of which

the above is a type) is the large number of degenerated fibres passing from the area of the cortical lesion over the middle line in the corpus callosum and down the internal capsule of the opposite side." He had found the same thing previously in the dog—degeneration in the internal capsule of both sides after unilateral lesions in the brain of the dog. In the dog all the degeneration of the opposite side ended in the optic thalamus. In the above experiment (extirpation of the left thumb area in the monkey) which he describes as the type of of a group the full results of which are promised in a later paper, some of the fibres which crossed in the corpus callosum ended in the superior temporal convolution, but all the rest passed into the thalamus; in a few animals, however, in which practically the same area was extirpated, some of the degenerated fibres found in the internal capsule of the opposite side could be followed through the pons and medulla oblongata into the cervical region of the cord, where they disappeared.

Mellus believes, then, that the decussation of the pyramidal fibres is not confined to the lower part of the medulla oblongata, but takes place even as high as the corpus callosum. This would seem to support to a certain extent the old view of Hamilton.

Grünbaum and Sherrington (68) have quite recently (1901) found that in the case of the higher apes extirpation of the "hand area," for example, on one side shows from examination by the Marchi method a large direct anterior pyramidal tract, a direct lateral and a crossed lateral pyramidal tract, occupying in transverse sections of the spinal cord about the same relative areas as in man. The crossed pyramidal tract from the "hand area" lesion was clearly traceable to the lumbar region of the cord. In the lowest brachial segments there was obvious degeneration of fibres in the grey matter of the ventral horn of the crossed side. Some of the large nerve cells also seemed degenerated. A lesion at the top of the precentral gyrus (that is, within the "leg area") gave no ventral pyramidal tract degeneration and only a very slight uncrossed lateral pyramidal, although an extensive crossed lateral pyramidal tract that descended through the whole length of the cord. It does seem extraordinary that a lesion strictly confined to the "hand

area" should give rise to a degeneration of the crossed pyramidal tract which extended to the lumbar region of the cord, and any possibility of injury to the "leg area" in the course of the operation would have to be excluded before absolute reliance could be placed on these findings.

In addition to the embryonic method of Flechsig and the degeneration method of Waller already described, may be mentioned the *atrophic or non-developmental method of von Gudden*, first employed by him in 1872. This consists in removing from a newly born animal certain parts of the central nervous system and allowing the animal to live, if possible, till it has reached the adult stage, or at least for several months. It is then killed, and the parts which have remained undeveloped as a result of the operation are held to be directly connected functionally with the part removed in early life. Von Gudden and von Monakow have been the chief workers along these lines. In 1872 von Gudden (69) removed the frontal area of one cerebral hemisphere in rabbits and dogs one day after birth. He allowed them to live for several months, and then on killing them found that the corresponding pyramid was atrophied or non-developed. From this he concluded that the fibres which go to make up the pyramids have their origin in the anterior part of the cerebral cortex.

Von Monakow (70) in 1884 experimented in a similar way on two cats and two rabbits. He found atrophy of the corresponding anterior pyramids in the medulla and pons and of the crossed pyramidal tract in the cord. He also observed atrophy in the grey matter of the corresponding optic thalamus and in the substantia nigra of the mid-brain of the same side, but he emphasises the fact that he could distinguish no difference between the two anterior cornua of the spinal cord; the cells and grey matter had quite a normal appearance on the two sides, whereas on the side of the cord opposite to the cortical lesion the grey matter in the region of the processus reticularis and lateral horn was markedly atrophied. From this he concluded that the pyramidal fibres are directly connected with the grey matter in the lateral horn, and not directly with the anterior cornua of the spinal cord. The conclusions which he arrived at at that time have been borne out by the results of much work

done subsequently, and the whole matter is gone into very fully in an extensive article published by him in the *Archiv für Psychiatrie* for 1895.

From the preceding account of the most important work which has been done upon this subject from the time of Türck down to the present day, it will be seen that the view taken by most neurologists, and supported by the observations of Mellus, Hoche, Romanow and others is, that there are only two sets of neurones on the motor path, whereas there are at least three on the sensory path. The advocates of this view teach that the pyramidal fibres, either by means of collaterals or of terminal fibres, form synapses around the cells of the cranial motor nuclei and of the anterior cornua of the spinal cord. Those fibres which end in relation to the cells of the cranial motor nuclei leave the pyramidal bundles in the pons and medulla oblongata, and crossing the median raphe, either as single fibres or in very small bundles, arborise around the cells of the nuclei of the opposite side, a few passing to the nuclei of the same side. The fibres destined for the anterior cornual cells of the spinal cord cross the middle line at the pyramidal decussation in the lower part of the medulla oblongata, and running down the crossed pyramidal tract of the opposite side of the cord, eventually arborise round the cells of the anterior horn of that side. A few, however, (homolateral fibres) do not cross in the decussation, but run down the lateral pyramidal tract of the same side to end in a similar way on that side. Thus the motor nuclei and the anterior cornual cells of both sides are related to one cerebral hemisphere.

Other authorities, notably von Monakow, Redlich and Schäfer, do not accept this view. They seem to believe that in the spinal cord at all events a distributive intermediate neurone is intercalated between the pyramidal fibres and the lower motor neurones, by means of which a single pyramidal fibre may be brought into functional relationship with many peripheral motor neurones. Von Monakow states, for example, that he has never been able to make out any direct connection between the pyramidal fibres and the anterior cornual cells, but that, instead of passing to the anterior horn, they appear to go to the processus reticularis near the lateral horn, and end in relation to cells in

this region. In this he is supported by Schäfer (71), who found in the monkey, by the Marchi method, fibres from the degenerated pyramidal tract in the cervical enlargement (the degeneration was due to hemisection of the spinal cord at a higher level) passing into the base of the posterior horn, but was not able to trace any to the anterior horn. Quite recently, however, Sherrington (72) says that in the higher apes, as the result of lesions in the "hand" area, he has found that "in the lowest brachial segments there is obvious degeneration of fibres in the grey matter of the ventral horn of the crossed side. Some of the large nerve cells also seemed degenerated." This, then, is how the matter stands at the present time, and it was with the object of throwing some light upon the question if possible that the work about to be recorded was undertaken.

Part II.

Method and Results of Research.

The animals experimented upon were cats and monkeys, and in all an attempt was made to divide the projection fibres arising from the left motor cortex in its whole extent. In one case Professor Schäfer was good enough to place at my disposal the brain and spinal cord of a dog in which he had, in the course of another investigation, made a lesion in the left motor cortex. I examined the secondary degeneration following from the lesion, and will include the results in this communication.

Operative procedure.—In every case the animal was fully anæsthetised with ether before the operation was begun, and was kept under the influence of the anæsthetic until it was completed and the wound closed and dressed. The hair was cut short and then shaved off the left side of the skull. The skin was thoroughly washed with soap and warm water, and finally with 1 in 20 carbolic lotion. A rectangular shaped incision was made through the integument, and a skin flap reflected downwards. The bone was bared by scraping the muscles and fasciæ from their attachments, and a trephine opening was then made through the bone as nearly as possible over the area of the brain

which it was desired to expose, and, if necessary, this opening was enlarged with bone forceps. Very frequently, especially in cats, there was much bleeding at this stage from the diploe, which in the skull of this animal is very thick, and this was arrested by applying some sterilised cotton-wool, previously soaked in a 5% solution of calcium chloride, to the face of the bone, with pressure. When the bleeding had stopped the dura mater was reflected, and the lesion produced in the following manner. Sheathed platinum electrodes were applied to the anterior portion of the exposed cortex and the motor area localised by stimulating with a fairly weak faradic current. A fine blunt-pointed bistoury was pushed obliquely downwards and forwards through the grey matter to the depth of about ¾ inch into the white matter close to the supero-mesial border of the left hemisphere, and then carried outwards just behind the posterior limit of the motor area. In this way a deep incision was made, cutting across all the motor fibres from the left hemisphere. The depth of the incision was always gauged on a formol-hardened brain before the knife was pushed into the living brain, and care was taken to avoid injury to the large vessels at the base. After the bleeding had stopped completely, but not until then, the dura was replaced and the skin wound closed with horsehair sutures. It was then covered with antiseptic gauze and sealed with collodion. The method of "under-cutting" the motor area instead of totally removing it was adopted with a view to avoid as far as possible any serious functional disturbance of the hemisphere, vascular or mechanical, and so to determine the effects produced upon sensation by a purely motor lesion.

The animals were allowed to live from fourteen to thirty-three days after the lesion had been produced, and during this time they were carefully examined for symptoms. They were then killed by an overdose of chloroform, the brain and spinal cord removed immediately after death, and hardened in most cases in Müller's fluid.

Histological technique.—The parts to be examined were stained by the method of Marchi. This method, first employed by Marchi (73) in 1887, and described in detail in his paper, is as follows:—After the brain or spinal cord has been partially

hardened in Müller's fluid, or a 2 per cent. potassium brichromate solution, for about ten days, it is cut into thin slices not more than $\frac{1}{8}$ inch thick and placed in Marchi's fluid, which consists of a mixture of Müller's fluid 2 parts, 1 per cent. osmic acid solution 1 part. In this mixture it is allowed to remain for ten days more. There must be excess of the fluid—not less than twenty times the volume of the tissue. A ground glass stoppered bottle must be used perfectly airtight to prevent evaporation of the osmic acid, and it must be kept in the dark to prevent its decomposition. At the end of about ten days the pieces of tissue are removed from the osmo-bichromate fluid, when they will be found to be quite black, washed in running water for a few hours, then placed in 75 per cent. alcohol, carried up the alcohol-xylol-paraffin series, and embedded and cut in paraffin. No subsequent staining is needed; the myelin of those nerve fibres which are in the process of degeneration is rendered black, while the normal nerve fibres remain unstained or have a faint yellow colour, due to the Müller's fluid.

The great disadvantage of this method is that in the above mixture the osmic acid has very little penetrating power, and for this reason the tissues must be cut into very thin slices, otherwise the centre of each piece will not be stained, and this is a great drawback, especially when it is necessary to make serial sections, as much of the tissue is lost in the process of paring the ends. Orr (74) states that by using a mixture of acetic acid and osmic acid the penetrating power of the latter is much increased. I have tried Orr's fluid in several cases, but have not found the results very satisfactory. I have also used Vassale's (75) fluid (made by adding to Marchi's solution a small quantity of nitric acid), which is said by him to increase the rapidity of action of the osmic acid, but the staining was not so successful as when Marchi's method was employed unmodified. My best results were obtained from fluid which had been used several times, each time about $\frac{1}{8}$ of its volume of a 1 per cent. solution of osmic acid being added before the tissues were immersed in it. For bringing out fine degeneration this was found to be much superior to freshly prepared Marchi solution. In a few cases the parts of the brain and spinal cord to be examined for degeneration were fixed in a 5 per cent. solution of

formalin instead of Müller's fluid before treatment by the Marchi method, but the staining was often found to be very uncertain, and this was soon abandoned.

After being cut in paraffin, the usual proceeding is to float the sections out on warm water, either in a tray or on the slide, in order to remove the folds in the paraffin and to fix the section to the slide. After this the section has to be thoroughly dried, either in an oven at a temperature of from 30° to 40° C. for at least half-an-hour, or at the room temperature overnight. I found that in the case of such a compact tissue as the brain or spinal cord, this spreading of the sections on water was not necessary. The sections were transferred directly from the paraffin ribbon to the slide, and then the paraffin at once dissolved off by a few drops of xylol from a pipette-bottle. After the paraffin had all been removed in this way, the section (or sections, several being mounted on the same slide), floating in a pool of xylol, was placed in position, the xylol was drained off at one end by a strip of blotting-paper, some thick Canada balsam was placed on a cover-glass, and then, when the section was just on the point of becoming dry, the cover-glass was inverted and placed on it. This method of procedure was found to save much time and to give good results. The sections were more transparent than when mounted in the ordinary way, and this was a great advantage, as it enabled one to cut and examine very thick sections in which any collateral or branching fibres that happened to be running obliquely could be traced for a much greater distance than in thin sections. The Cambridge rocking microtome was used throughout.

The method of examination for the physiological symptoms which might have resulted from the lesions was as follows:—

Motor.—If the animal was tame and quiet it was taken out of the cage and allowed to move about the room, when its general attitude and mode of walking were observed. In the case of monkeys the manner in which they used their limbs in climbing was noted. To test voluntary power in the arms, the animal (monkey) was offered a small piece of banana or apple, or a few currants were placed upon the floor within its reach, and its ability or inability to take hold of or pick up these was noted. In the case of the hind limbs, the animal was lifted up and

gently swung towards the wire-netting of the cage, or dropped towards (but not on to) the floor. If an animal suspended in this way possesses the power of voluntarily moving its limbs, both are extended towards the cage or floor, but if voluntary power is absent in one or other of the limbs there is no such movement of that limb, and besides, the paralysed limb hangs pendulous, while the non-paralysed limbs are usually somewhat drawn up. Voluntary power is much more easily tested in the monkey than in the cat, but when the latter is suddenly dropped towards the floor (on all fours) there may be no movement of the unaffected limb or limbs as a whole, but in the normal animal the toes are always extended and spread out as the foot approaches the ground, *i.e.* an attempt is made to catch the floor. No such movement of the toes, however, is observed in a paralysed limb. To test the *grasping power* (in monkeys) a small stick, or preferably the observer's finger, was held out to the animal, and its power of *hanging on* to any object which it had seized, such as the wire-netting of the cage, was also noted.

Sensory.—In testing *general sensibility* the part to be examined was touched or stroked lightly (not pricked) with a needle at the end of a long stick, while the attention of the animal was attracted by an assistant, so that it might not *see* that it was being touched. If tactile sensation was not absent, the animal looked round and withdrew the limb, or indicated by some gesture that it felt the touch. To test whether pain was felt it was pricked with the needle. The plan generally adopted was to test for pain first, for after an animal has been pricked once or twice it responds more readily to a simple touch, probably from apprehension of a prick. The "clip-test" introduced by Schiff, and relied on by Mott and others, was also employed, but, as pointed out by Schäfer, it is misleading, and want of response to this test indicates motor rather than sensory paralysis. If a strong steel clip is applied to the skin while the animal does not see what is being done, an attempt will be made instantly to remove it from a sound limb, but if the limb is paralysed no notice may be taken of it. Often it was found that an animal would respond to a simple touch, while it would take no notice of a strong steel clip, thus showing the fallacy of this test.

In examining as to whether the sensations of *heat* and *cold*

were affected, the animal was suspended in a sling-jacket, and when perfectly quiet a vessel containing hot or cold water was brought up underneath it until the fingers or toes dipped into the water. If sensation was present the limb was withdrawn, or, if there was voluntary paralysis of that limb, the animal indicated by struggling or otherwise that it felt the hot or cold water. It was found in every case that the animal responded when hot water was applied to the foot or hand, but on the paralysed side the sensation was often delayed for a surprisingly long time—in some cases as long as twenty seconds. The *knee-jerk* reflex was examined in the usual way. The *temperature* of the rectum, axilla, anticubital fossa, groin and popliteal space was taken from time to time, and the condition of the pupils and of visual sensation was also examined.

When the animal was killed, and again after the brain had been partially hardened in Müller's fluid, the position and extent of the lesion was examined so as to be accurately located, and in as many cases as possible photographs of the brain were taken before it was cut up and placed in Marchi's solution. In these photographs the superficial area of the brain to which the dura mater had become adherent after the operation is shown, and also the depth to which the gross effects of the lesion had extended into the corona radiata. To the naked eye the latter was often visible as a reddish-brown patch, due probably to blood extravasation.

Physiological and Anatomical Effects of Lesions.

As the lesion was practically the same in each case it will be sufficient to describe in detail the results obtained in a single typical example from each set of animals experimented upon. The symptoms varied considerably in the different cases, and to a much smaller extent the degenerations also, but these variations will be taken note of in the general summary at the end of the paper.

Cat No. V.

Lesion.—The fibres from the left motor cortex were severed by an incision into the white matter behind the motor area, as

already described. When the animal was killed the dura mater was found to be adherent to the cortex over an area involving the posterior limb of the sigmoid gyrus and the anterior extremities of the first, second and third convolutions on the left side. On slicing away the anterior part of the left hemisphere the gross lesion was seen to extend into the corona radiata for some distance, but it did not reach so far back as the head of the caudate nucleus, and the basal ganglia were not involved at all. The animal was killed fourteen days after the operation.

Symptoms during life.—There was paralysis of all purely voluntary movements in both right limbs. At first the animal was lame on the right side, but this was gradually recovered from. Tactile sensation was absent for the first few days in the right fore-leg and diminished in the right hind-leg, but it was completely restored in both before the animal was killed. To cold there was response at once, but to heat there was some delay, and immersion of the toes of the affected limbs in water at 57° C. at the end of a few seconds, during which the animal took no notice, seemed suddenly to give rise to acute pain. There was no hemianopsia in this case, although it was found in not a few of the others.

Secondary Degeneration.—T. S. Mesencephalon through anterior corpora quadrigemina (fig. 1).—The left crusta shows uniform degeneration throughout its whole extent, with the exception of a narrow zone along its ventro-lateral border, which contains only a very few degenerated fibres. There is much fine degeneration in the substantia nigra on the side of the lesion. From the crusta many degenerated fibres are seen streaming off into the tegmentum, and passing backwards towards the anterior corpus quadrigeminum of the same side. These come off most abundantly from the outer extremity of the crusta, but many are seen passing backwards from the whole extent of its posterior border, and they all run towards the anterior corpus quadrigeminum in the grey matter of which they appear to terminate; there is a small amount of fine degeneration in this grey matter. Those fibres from the mesial extremity of the crusta pass backwards close to the central grey matter around the Sylvian aqueduct, and one or two fibres pass through the lateral part of this grey matter, but all are directed towards the quadrigeminal

body of the left side. Some black granules are visible in the emerging roots of the third nerve and descending root of the fifth on each side, and also in the bundles of Meynert's decussation on the left side, but these are deposited irregularly, and do not represent degenerated nerve fibres.

Transverse section through upper part of pons Varolii and post. corp. quad.—The whole left crusta which is just passing into the pons is degenerated. A few fibres pass backwards from its outer angle into the tegmentum, but they cannot be traced to any distance. No fibres can be seen passing backwards towards the posterior corpus quadrigeminum, and there is no fine degeneration in its grey matter. Very abundant fine degeneration is seen around the cells of the nuclei pontis, which lie amongst the transverse fibres of the pons just in front of the degenerated crusta, and this is strictly limited to the side of the lesion. There is no fine degeneration in the central grey matter.

T. S. through middle of pons (fig. 2).—All the pyramidal bundles on the left side (side of lesion) are filled with degenerated fibres, and the degeneration invades to a slight extent the lateral portion of the mesial fillet. There is very abundant fine degeneration scattered amongst the cells of the nuclei pontis laterally, anteriorly and mesially to the pyramidal bundles. This fine degeneration stops abruptly at the median raphe, and none is visible on the opposite side. There is no evidence of any fine degeneration in the grey matter of the floor of the fourth ventricle.

T. S. through lower part of pons.—The left anterior pyramid (which is just about to reach the surface, and which appears smaller to the naked eye than the right) shows uniform and extensive degeneration. From the postero-mesial angle of the degenerated pyramid a small bundle of fibres passes off, and immediately crossing the middle line, disappears in the formatio reticularis of the opposite side. In addition to these, one or two degenerated fibres run directly backwards, and quickly disappear in the reticular formation of the same side.

T. S. of medulla oblongata through the middle of the inferior olivary nucleus.—The left anterior pyramid is extensively degenerated as in the last section, and coming off from its postero-internal angle there are a few degenerated fibres which cross

the middle line well forward, and passing through the opposite olivary nucleus, disappear in the formatio reticularis immediately behind that nucleus. One or two fibres come off from the posterior aspect of the degenerated pyramid, and running backwards and outwards through the olivary nucleus of the same side, are lost in the formatio reticularis behind it.

T. S. of medulla oblongata about the middle of the pyramidal decussation.—The left pyramid is studded with degenerated fibres, and a large bundle is seen to pass obliquely across the middle line, interlacing with a similar bundle of undegenerated fibres from the opposite pyramid. At first it passes backwards close to the antero-lateral aspect of the central canal, and then it curves more lateralwards towards the region of the substantia gelatinosa of Rolando. Some degenerated fibres (homolateral) are seen curving round towards the left side, and running along with the decussated fibres from the right pyramid.

T. S. of medulla oblongata about the level of the lower extremity of the pyramidal decussation (fig. 3).—A narrow area of degeneration is seen bordering the anterior median fissure on the left side; this is all that remains of the left anterior pyramid. From the posterior extremity of this area two or three small bundles of degenerated fibres cross the middle line. These bundles run at first backwards and then curve outwards, and passing through the grey matter, join bundles of transversely cut fibres at the base of the substantia gelatinosa of Rolando, and in the inner portion of the lateral column of the opposite side, which have decussated at a higher level. These fibres will go to form the right crossed pyramidal tract of the spinal cord at a slightly lower level. One or two homolateral fibres can be seen passing through the grey matter towards the crossed pyramidal tract of the same (left) side, but in this animal these homolateral fibres are not very abundant.

T. S. of spinal cord through the 6th cervical segment (fig. 4).—In the posterior portion of the right lateral column is seen a rounded area of degeneration abutting against the apex of the posterior horn, but not reaching quite to the circumference of the section. From its mesial aspect a few fibres, cut somewhat obliquely, pass in towards the base of the posterior horn and processus reticularis, and in the grey matter of these regions

there is a considerable amount of fine or terminal degeneration. A few homolateral degenerated fibres are visible in the left lateral column, but no unerossed fibres are to be found in the left anterior column, that is to say, there is a direct lateral column pyramidal tract, but no direct anterior column tract.

T. S. of spinal cord through mid-dorsal region (fig. 5).—The rounded area of degeneration occupied by the right crossed pyramidal tract at this level lies antero-lateral to the tip of the posterior horn. It is considerably smaller than in the cervical region, and no fibres can be made out passing from its inner aspect towards the base of the posterior horn, such as those described in the last section.

T. S. of spinal cord through the 3rd lumbar segment (fig. 6).—The right (degenerated) crossed pyramidal tract occupies the same relative position as in the dorsal region; it is considerably smaller in area, and the degenerated fibres within the area are not so numerous. One or two obliquely cut fibres pass in towards the base of the posterior horn as in the cervical region, and a few homolateral fibres are seen in this and the last section uniformly scattered over the area of the left crossed pyramidal tract.

Dog.

The material from this animal (which was the only dog examined) was given me by Professor Schäfer in order that I might report upon the secondary degeneration resulting from the lesion, which was a deep circumsection of the left sigmoid gyrus. The following is a description of the lesion and the symptoms resulting from it given by Professor Schäfer in the *Proceedings of the Physiological Society*, Jan. 26th, 1901:—"In the dog experimented on, a cut 5–7 mm. deep was made well around the sigmoid gyrus. The result of this was to produce paralysis for voluntary motion (inability to hold a bone, awkwardness in walking) and blunted sensibility on the opposite side, and also at first homonymous hemianopsia, which however had disappeared on the fifth day. The animal was killed one month after the operation; the circumsected area gave no result on stimulation."

Secondary Degeneration.—Coronal section through posterior part

of optic thalamus and internal capsule.—The bundles of the internal capsule on the left side (side of lesion) are markedly degenerated throughout its middle three-fifths, and from these bundles some fibres run into the grey matter of the optic thalamus, in which they appear to end. There is a considerable amount of fine degeneration in the grey matter of the outer half of the thalamus. The internal capsule on the opposite side is free from degeneration, as also is the grey matter of the optic thalamus on that side.

T. S. of mesencephalon through the anterior part of the anterior corpora quadrigemina.—This section is somewhat oblique, and includes the external geniculate body on the right side, with a small segment of the optic tract. The left crusta shows extensive degeneration with the exception of its external margin, and there are some detached bundles of degenerated fibres transversely cut passing downwards (caudalwards) in the substantia nigra, immediately behind the crusta. There is a very small amount of fine degeneration amongst the grey matter of the substantia nigra opposite the lateral part of the crusta, but no fibres are visible passing backwards through the substantia nigra into the tegmentum, as was the case in most of the cats examined. No fine degeneration is visible either in the central grey matter or in that of the anterior corpora quadrigemina.

T. S. of upper part of pons Varolii.—The left crusta is just about to pass into the substance of the pons and become broken up into the pyramidal bundles; it is degenerated throughout its whole extent; some of the fibres along its antero-lateral margin are cut obliquely. There is a slight amount of fine degeneration opposite the internal extremity of the crusta, amongst the transverse fibres of the pons.

T. S. through middle of pons (figs. 7 and 8).—This shows the pyramidal bundles on the left side extensively degenerated, and all around these, but especially on the mesial and antero-external aspects, there is very abundant fine degeneration amongst the cells of the nuclei pontis. This fine degeneration is exceedingly well marked in this animal. No fibres are seen passing backwards from the degenerated bundles, and no fine degeneration is visible in the grey matter of the floor of the fourth ventricle.

T. S. of medulla oblongata through the upper part.—The left

pyramid shows extensive and uniform degeneration throughout the whole area of its transverse section, and from its posterior aspect many fibres run backwards through the internal arcuate fibres, and after crossing the median raphe, are lost in the formatio reticularis of the opposite side, while a few end in that of the same side. A few degenerated fibres are found in the posterior longitudinal bundle on each side.

T. S. of medulla oblongata through the middle of the inferior olivary nucleus.—The description given of the last section also applies to this. In this specimen the hypoglossal nucleus and the emerging roots of the nerve are well seen on each side, and a few black granules are deposited amongst the root fibres, but these do not represent degenerated fibres. There is no trace of any fibres from the degenerated pyramid passing towards or near the hypoglossal nuclei.

Transverse sections through lower part of medulla oblongata.—In this specimen there are several sections taken through the pyramidal decussation at different levels, and in each the comparatively large bundles of crossing and crossed fibres are seen passing through the grey matter towards the lateral column of the opposite side, and a few homolateral fibres passing to that of the same side, and joining the transversely cut fibres that have crossed at a higher level.

T. S. of spinal cord through the 1st cervical segment.—The degenerated crossed pyramidal tract occupies a rounded area in the posterior part of the right lateral column, in close contact with the lateral border of the posterior horn. One or two detached bundles lie within the grey matter at the base of the posterior horn; these have not yet joined the main mass of degenerated fibres which go to make up the crossed pyramidal tract. There is a considerable area free from degeneration between the crossed pyramidal tract and the margin of the section. A few degenerated fibres are scattered throughout an area on the left side corresponding to that of the degenerated tract on the right. There is no trace of a direct (anterior) pyramidal tract at this level, all the fibres having crossed higher up except the homolateral fibres found in the left lateral column.

T. S. of spinal cord through the 6th cervical segment.—A rounded patch of degeneration is situated in the posterior part

of the right lateral column; it does not reach either the posterior horn or the free margin of the section. No fibres can be made out going towards the base of the posterior horn, and there is no fine degeneration in its grey matter. About a dozen degenerated homolateral fibres are to be found in the crossed pyramidal tract on the left side.

T. S. of spinal cord through the 6th dorsal segment.—The crossed pyramidal tract is much reduced in size and the degenerated fibres are not so thickly studded over its area, but it occupies the same relative position as in the last section. There are still a few degenerated fibres scattered amongst the normal fibres of the crossed pyramidal tract of the left side.

T. S. of spinal cord through the 3rd lumbar segment.—The degenerated crossed pyramidal tract is still smaller in area and contains fewer fibres than in sections through the mid-dorsal region, and at this level one or two can be seen to pass into the grey matter at the base of the posterior horn. Not more than three or four homolateral fibres remain on the left side.

Monkey No. I. (*Macacus rhæsus*)—*Male.*

Lesion.—The motor projection fibres from the left Rolandic area were cut across as described previously by making an oblique incision just behind and parallel with the posterior border of the ascending parietal convolution. The incision extended from a point close to the supero-mesial border of the left hemisphere downwards and forwards to a point near the Sylvian fissure. On post-mortem examination, the dura mater was found to be adherent over the ascending frontal and parietal convolutions on the left side. The animal was allowed to live thirty-one days after the operation, and was then killed by an overdose of chloroform.

Symptoms.—There was right-sided voluntary motor paralysis and sensory (tactile) paralysis of the hind limb. To the "clip test" and cold water there was no response in either right limb, while there was response, but only after a delay of several seconds, to the hot-water test. The knee-jerk was exaggerated on the right side. The sensory disturbance passed off to

a considerable extent before the animal was killed and the power of walking and climbing improved, but power of performing voluntary unassociated movements did not return in the right limb.

Secondary Degeneration.—Coronal section through posterior region of optic thalamus.—(This section was imperfectly penetrated by the osmic acid.)—The internal capsule on the left side shows marked degeneration throughout its greater extent, but a small part anteriorly is free from degeneration. Mesial to the capsule in the lateral part of the grey matter of the optic thalamus there is a considerable amount of fine degeneration.

T. S. of mesencephalon through anterior corpora quadrigemina.—The left crusta contains numerous degenerated fibres thickly and uniformly scattered over its middle three-fifths, while its most lateral and mesial fifths are practically free from degeneration. There is a slight amount of fine degeneration in the substantia nigra immediately behind the crusta, but no fibres are seen passing backwards into the tegmentum, either towards the anterior corpus quadrigeminum or towards the central grey matter. The cells of the nucleus of the oculo-motor nerve are well seen on each side, but there is no trace of any fine degeneration amongst them.

T. S. through the upper part of the pons Varolii (figs. 9 and 10).—On the side of the lesion the pyramidal bundles are studded with transversely cut fibres, but these are less numerous in the more lateral bundles than in the others. There is a considerable number of degenerated fibres in the lateral portion of the mesial fillet just behind the pyramidal bundles, and in addition there is very extensive fine degeneration amongst the cells of the nuclei pontis, most marked in the mesial region, but not extending across the middle line.

T. S. through the lower part of the pons.—At this level the pyramidal bundles have just become reunited to form the anterior pyramids which are about to reach the surface. The left pyramid is filled with degenerated fibres, and from its postero-internal angle one or two run backwards and inwards, but these cannot be traced across the middle line. Scattered amongst the transverse fibres of the pons behind the degenerated pyramid there is a very slight amount of fine degeneration.

T. S. of medulla oblongata through middle of inferior olive (fig. 11).—The left anterior pyramid is here again completely degenerated, and from its postero-mesial angle a few fibres pass backwards, and then crossing the median raphe, are lost in the reticular formation of the opposite side, while one or two run backwards and outwards and disappear in that of the same side.

T. S. of medulla oblongata through upper part of pyramidal decussation (fig. 12).—A few bundles of degenerated fibres cross the middle line, intermingling with normal fibres from the opposite (right) pyramid; they disappear amongst the internal arcuate fibres on the right side close to the middle line. No homolateral fibres are visible at this level in this particular animal.

T. S. of medulla oblongata through middle of pyramidal decussation.—The left pyramid is very much reduced in size, and a very large bundle of degenerated fibres is seen crossing the middle line, interlacing with similar bundles from the normal pyramid. Numerous large fasciculi of degenerated fibres cut transversely are situated within the grey matter lateral to the central canal; these consist of fibres which have crossed at a higher level and are now descending to reach the crossed pyramidal tract of the spinal cord. A few homolateral fibres are also visible, taking up a similar position on the side of the lesion.

In sections passing through the lower parts of the decussation (fig. 13) the pyramid becomes smaller and smaller in size, and the crossed and homolateral fibres situated in what corresponds to the lateral columns of the spinal cord become more and more numerous. These take up a position on either side antero-mesial to the substantia gelatinosa of Rolando.

T. S. of spinal cord through the 1st cervical segment.—Bundles of transversely cut degenerated fibres lie amongst the grey matter at the base of the tubercle of Rolando on the right side; these are passing down to reach the lateral column at a lower level. A few homolateral fibres occupy a corresponding position on the left side. Degenerated fibres now extend to the margin of the section.

T. S. of spinal cord through the 6th cervical segment (fig. 14).—

The crossed pyramidal tract on the right side is now apparent as a wedge-shaped area filled with degenerated fibres, quite unlike the rounded area in the cat and dog, and absolutely and relatively to the rest of the lateral column much more extensive. The direct cerebellar tract is practically free from degeneration. A few fibres cut obliquely can be seen passing from the degenerated tract towards the base of the posterior horn, and a considerable amount of fine degeneration is present in the grey matter of the posterior horn on that side, while none is visible in any other part. Some homolateral fibres are found on the same side as the lesion.

T. S. of spinal cord through the 6th dorsal segment.—The degenerated pyramidal tract is smaller in area and now reaches almost to the margin of the lateral column, the direct cerebellar tract being very narrow at this level. Homolateral fibres on the opposite side are much fewer in number than in the cervical region. No fibres can be seen entering the grey matter.

T. S. of spinal cord through the 3rd lumbar segment (fig. 18).—A few fibres can be traced from the degenerated crossed pyramidal tract into the grey matter at the base of the posterior horn, and in this grey matter there is a small amount of fine degeneration. About a dozen homolateral fibres can be counted on the left side.

T. S. of spinal cord through 4th sacral segment (fig. 19).—This section shows about thirty crossed and four or five direct lateral pyramidal fibres degenerated.

General Summary of the Results obtained and Conclusions based thereon.

Physiological.—A complete severance of the projection fibres arising from the motor cortex on one side, with as little injury to adjacent parts as was practically possible, was found to be followed by motor paralysis of the opposite side of the body. The power of walking, climbing, etc. was to a large extent restored before the animals were killed, but voluntary power, *i.e.* the power to perform purely voluntary "isolated or unassociated movements," such as picking up food, etc., did not return, or if at all, only in a very slight degree. In cats, "associated move-

ments," such as walking, climbing, jumping, etc., were never so much affected as in monkeys, and returned much earlier.

With regard to the sensory effects, a great variety of symptoms were produced in the different animals by what, upon macroscopic and microsopic examination, were found to be practically similar lesions. As a rule, in the parts showing motor paralysis or paresis there was also blunted or abolished tactile sensibility, but in some cases there was complete motor paralysis while general sensibility in the affected limbs appeared to be quite normal, and in one or two cases the affected side was distinctly more sensitive to tactile impressions than the normal side. As a rule, tactile sensory paralysis disappeared rapidly, and sensation in most cases was completely restored within a fortnight. With regard to the temperature sense, cold impressions in many of the cases produced no effect, but in no case was there paralysis of the sensation of heat, although it was often delayed for a surprisingly long time, and after the delay it was usually felt as *pain* and not warmth, as indicated by the fact that the animal struggled or uttered cries. In some cases there was homonymous hemianopsia—always right-sided from a left-sided lesion—although the post-mortem examination showed no injury to the occipital lobe, optic thalamus, or any other part of the optic system. In one cat it lasted as long as the animal lived, but in the other cases in which it was present it passed off within a few days. In most of the cases examined the temperature of the paralysed limbs was lower than that of the sound side, but in one case it was higher. These differences in temperature between the two sides of the body soon passed off, indicating that the vaso-motor disturbances which had been the probable cause of it had disappeared. The knee-jerk was always brisker on the paralysed than on the sound side.

The fact that motor and sensory paralyses do not always go together, sometimes motor paralysis being complete, while sensation is unaffected, would appear to prove conclusively that the cortex of the Rolandic area cannot be the sole centre for tactile sensation, as it is stated to be by Munk (76), Mott (77), and many other eminent neurologists, but that this must be sought for in some other part of the hemispheric ganglion. The transient sensory disturbances that often follow motor cortical

lesions may, as pointed out by Schäfer (78), be due to slight unavoidable injury to other parts of the hemisphere, or to altered mechanical or vascular conditions produced by the operation, and when these conditions return to the normal, the sensory paralysis passes off, while the motor remains. They may, however, have a more far-reaching cause, as is shown by the fact that they are often accompanied by hemianopsia. This has been recorded by Mott, and by Ferrier and Turner, and has recently been emphasised by Hitzig.

2. *Anatomical.*—In the cat, as the result of a lesion cutting off the whole left motor cortex, degeneration was found in the internal capsule of the same side, occupying about the middle three-fifths of its whole extent, the anterior and posterior (superior and inferior in the cat) extremities being free. [In only two cats were sections made through the internal capsule and thalamencephalon.] Degenerated fibres were found passing from the centrum ovale through the corpus callosum to the right hemisphere, but none were seen to turn down into the right internal capsule. Opposite the posterior part of the left optic thalamus some fibres leave the capsule, the bundles of which are at this level becoming compacted together to form the crusta, and passing into the grey matter of this and the subthalamic region appear to end there, as indicated by the presence of a considerable quantity of fine or terminal degeneration. In the upper levels of the mesencephalon the whole of the left crusta is degenerated, with the exception of a narrow marginal area along its antero-lateral border. From the posterior aspect of the crusta numerous degenerated fibres pass backwards through the substantia nigra into and through the tegmentum, towards the anterior corpus quadrigeminum of the same side. These for the most part end in the grey matter of that body, but a few curve round close to its posterior or superior surface, and crossing in the roof of the aqueduct, are lost in the quadrigeminal body of the opposite side. In only one or two cases were any fibres seen to enter the central grey matter around the Sylvian aqueduct, and these did not appear to end there, but seemed to be continued through the lateral portion of it in their course towards the anterior corpus quadrigeminum. In every case there was a varying amount of fine degeneration

amongst the grey matter of the substantia nigra posterior (superior) to the degenerated crusta.

In the pons the pyramidal bundles were found to be uniformly degenerated on the side of the lesion, and surrounding these bundles, amongst the cells of the nuclei pontis through which they pass, a very large amount of fine or terminal degeneration was found in the case of every animal examined. No fibres were seen to pass backwards from the pontine pyramidal bundles towards the grey matter of the floor of the fourth ventricle as had been observed from the crusta in the mid-brain, and no fine degeneration was present in that grey matter. In the upper levels of the medulla oblongata, when the pontine bundles had united again to form the anterior pyramid, a few fibres begin to leave the posterior aspect of the degenerated pyramid, particularly from its postero-mesial angle; most of these cross the median raphe and are lost amongst the internal arcuate fibres of the formatio reticularis of the opposite (right) side, whilst some disappear in that of the same side. Similar fibres, very few in number however, continue to pass backwards from the degenerated pyramid throughout its whole extent in the bulb until the upper extremity of the true decussation is reached. They run, not towards the grey matter in the floor of the fourth ventricle or around the central canal in the closed part of the medulla, but more lateralwards towards the base of the substantia gelatinosa of Rolando. They cannot be traced far into the reticular formation. No fine degeneration could be made out in the grey matter of the floor of the fourth ventricle in any part of the medulla, although this was very carefully looked for. When the motor decussation proper is reached, bundles of fibres are observed to come off from the postero-internal angle of the degenerated pyramid, and after crossing the middle line, to pass backwards towards the lateral portion of the grey matter around the central canal, and then to curve more outwards and become lost as they turn caudalwards in their passage towards the lateral column (crossed pyramidal tract) of the spinal cord. With the exception of the few isolated fibres already described as leaving the pyramid at a higher level, hardly any homolateral fibres were seen coming off until the middle of the decussation was reached, and from this level downwards these homolateral

fibres increased in number. Redlich says that these homolateral fibres come off most abundantly from the middle two-fourths of the decussation. When this region of the medulla was cut serially, they were missed in several consecutive sections and then appeared again. This is due to the fact that they come off in small bundles comparatively widely separated from each other vertically. The ratio between the number of decussating and non-decussating fibres was found to vary considerably in the different animals examined; and with regard to this, the relative numbers can only be known by counting the fibres on each side in sections through the upper cervical segments of the spinal cord, and not by comparing the two sides in any one section through the decussation, a method which seems to have been adopted by some observers.

In the cervical region of the spinal cord the crossed pyramidal tract occupied a comparatively small rounded area in the posterior part of the lateral column on the right side, close to the antero-lateral aspect of the posterior horn, but not reaching the margin of the section. A few fibres were seen to pass in from the degenerated tract towards the base of the posterior horn, and some fine degeneration was present in this region of the grey matter. A few homolateral or uncrossed fibres, varying in number in the different animals examined, were found to occupy a corresponding position in the lateral column on the side of the lesion. In the dorsal, lumbar and sacral regions of the cord, fibres representing both direct and crossed lateral pyramidal tracts were found in gradually diminishing numbers, and both tracts were represented as far back as the fourth sacral segment, beyond which no section was examined.

In the case of the single dog examined the above description applies for the most part, but with one notable exception, viz., that no fibres could be observed passing backwards from the degenerated crusta in the mid-brain towards the anterior corpus quadrigeminum. There was in the pons the same amount of fine degeneration amongst the cells of the nuclei pontis; indeed this was more marked in the dog than in any of the cats examined.

In the monkey the degeneration occupied about the middle three-fifths of the crusta, and not its whole area with the

exception of a narrow margin along its antero-lateral border, as it was found to do in the cat and dog. Below the level of the mid-brain throughout the whole extent of the pyramidal tract in all the animals examined, the degeneration was scattered fairly uniformly over the whole area of its transverse section, with the exception of the pyramidal bundles in the pons, in which those situated most laterally contained fewer degenerated fibres than the others. As in the dog, no fibres could be found passing from the crusta to the grey matter of the anterior corpora quadrigemina, but there was abundant fine degeneration amongst the cells of the nuclei pontis on the side of the lesion, and no trace of any on the opposite side. In the spinal cord the pyramidal tracts, both crossed and uncrossed, are much more extensive in transverse section, and contain many more degenerated fibres than was found to be the case in the cat and dog. In the cervical and lumbar enlargements of the spinal cord some fibres from the degenerated tract could be made out, passing in towards the grey matter at the base of the posterior horn; these were more numerous in the cervical than in the lumbar region; in this grey matter, in both regions, there was a varying amount of fine degeneration, pointing to the fact that some fibres of the pyramidal tract probably terminated here.

For the most part the observations above recorded agree with those of former observers, but there are some points of difference to which special attention might be called.

1. The connection between the grey matter of the optic thalamus and the fibres of the pyramidal tract has been observed by von Monakow as early as 1884, and by Boyce, Mellus and others since then.

2. Monakow, Sherrington, Langley and Grünbaum, Mellus, Dejerine and Long, and others have found either atrophy of or fine (terminal) degeneration in the substantia nigra in relation to the degenerated crusta, according to the method employed.

3. With regard to the fibres in the cat which leave the degenerated crusta and pass backwards through the tegmentum to the anterior corpus quadrigeminum, only two observers, so far as I know, have called attention to them, viz., Boyce in the cat and Muratoff in the dog. Boyce found similar fibres in two out of four cats in which he had made lesions in the motor area and

examined by the Marchi method. He describes them as coming off from the outer extremity of the degenerated crusta. In the fourteen cases (all cats) examined by me, they leave the whole of the posterior aspect of the crusta as well as its outer extremity, and in many of these cases they were very numerous. Muratoff seems to have found them very scantily in the dog, for in the illustration which accompanies his paper only a single fibre is represented. I have found no trace of such fibres in either the dog or the two monkeys which I have examined, but I would be far from saying that they do not exist in these animals as well as in the cat. What particular region of the motor area they come from I have not been able as yet to determine, and what their significance is it is not possible to say. It may be that they are indirectly connected through the grey matter of the anterior corpora quadrigemina with the nuclei of the nerves which supply the muscles of the eyeball, that is to say, that a short neurone is interposed between their terminations in the anterior corpora quadrigemina and the cells of these nuclei. Another possibility is, that they may end in relation to the cells of origin of some other tract which starts in the anterior quadrigeminal bodies and passes down to lower levels in the medulla oblongata or spinal cord.

4. With the exception of Dejerine and Long in 1898, no one seems to have noticed or emphasised sufficiently the fine or terminal degeneration which is found in the nuclei pontis associated with motor cortical lesions. These observers, in material obtained from five cases of cerebral hemiplegia, and examined by the Marchi method, found such degeneration in two of the cases. In all the animals which I have examined—nineteen in number—this fine degeneration has been present, and often very abundant. Atrophy of the grey substance of the pons is often seen in old standing cases of hemiplegia, and therefore the cells of the nuclei pontis are supposed to have some connection with the pyramidal tract, but the extent and importance of this connection has not been sufficiently estimated. This is probably a very important cell station on the motor path.

5. I have never been able to trace any degenerated fibres from the main pyramidal tract to any of the cranial motor nuclei, as Mellus, Hoche and Romanow state that they have

succeeded in doing, nor have I found any trace of fine or terminal degeneration in the regions of the grey matter in which these nuclei are situated. Boyce and Dejerine and Long also expressly state that they have never been able to find any fibres going to the motor nuclei. In several cases I have cut in serial sections the whole of the mid-brain, pons and medulla oblongata, but in none of these have I ever found such fibres. To this it may be said that these nuclei are supplied by collateral or terminal fibres which are not readily revealed by the method of Marchi, but such fibres could be traced with the greatest ease from the crusta to the grey matter of the anterior corpora quadrigemina in the mid-brain, and it is remarkable, if they exist, that they cannot be found passing to the motor nuclei.

6. On comparing my sections through the pons and medulla oblongata with the figures given by Muratoff and by Romanow in their papers (on which these observers seem to base their statements that fibres from the pyramid pass to the motor nuclei in the medulla and pons), I found that there was a very close resemblance. It will be seen from these figures that, as in the sections I examined, the fibres in question are not directed towards the grey matter in which the cranial nuclei are situated, but seem, for the short distance to which they can be traced, to pass more lateralwards towards the substantia gelatinosa of Rolando. It is not improbable that these fibres which leave the pyramid, some crossing the median raphe and passing into the formatio reticularis of the opposite side, others passing to that of the same side, may be destined for the lateral columns of the spinal cord. The motor decussation may not be entirely confined to the lower part of the medulla oblongata, but may take place to a slight extent in the upper part as well, and even in the lower part of the pons. These may be homolateral and heterolateral spinal pyramidal tract fibres. The fibres which have crossed and are descending in the bulb on the opposite side might explain the significance of Pick's bundle, a fasciculus of fibres first described by Pick (79) in 1889 as ascending from the lateral column of the cord and ending in or near the nuclei of the posterior columns. Hoche (80) in 1898 described it as a descending tract, partly of pyramidal origin; and quite recently Barnes (81), who has investigated it, comes to the conclusion

that "it is probably an ascending tract which arises from the crossed pyramid at the decussation, and forms at least part of the pyramidal supply of the nucleus ambiguus; it is fairly frequently degenerated in cases of hemiplegia." So far, it has only been described in the human subject.

7. Fibres from the crossed pyramidal tract passing to the base of the posterior horn have been observed by Schäfer (71) in the monkey following hemisection of the cord at a higher level. I have had an opportunity of examining his specimens, and find that the fibres in question are more abundant than after motor cortical lesions, so that in the former case they are probably derived from more than one source. Sherrington (72), on the other hand, states that in the higher apes, as the result of cortical lesions in the "hand area," he has found "in the lowest brachial segments obvious degeneration of fibres in the grey matter of the ventral horn of the crossed side." This I have never seen in the cat, dog, or macaque monkey, but I have often observed fine degeneration in the grey matter at the base of the posterior horn on the crossed side in the cervical and, to a less extent, in the lumbar enlargement.

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DESCRIPTION OF THE FIGURES IN PLATES XIV. AND XV.

Fig. 1.—T.S. Mid-brain of cat at level of root of 3rd nerve, showing fibres passing from the degenerated crusta on the left side to the ant. corp. quad. of the same side, a few crossing to that of the opposite side in the roof of the aqueduct of Sylvius. × 10 diam.

Fig. 2.—T.S. Pons Varolii of cat, showing fine degeneration scattered around the degenerated pyramidal bundles on the left side (right in fig.). × 25 diam.

Fig. 3.—T.S. Medulla oblongata of cat through lowest part of pyramidal decussation, showing homolateral and heterolateral fibres. × 10 diam.

Fig. 4.—T.S. Spinal cord of cat through sixth cervical segment, showing fibres entering the base of the posterior horn from the right crossed pyramidal tract (left side in fig.), and fine degeneration in adjacent grey matter. × 10 diam.

Fig. 5.—T.S. Spinal cord of cat through mid-dorsal region, showing crossed and direct lateral pyramidal tracts. × 10 diam.

Fig. 6.—T.S. Spinal cord of cat through third lumbar segment, showing crossed and direct tracts with a few fibres passing into the grey matter at the base of the posterior horn on the right side. × 10 diam.

Fig. 7.—T.S. Pons Varolii of dog, showing fine degeneration scattered around the pyramidal bundles in the nuclei pontis. × 10 diam.

Fig. 8.—The same section. × 100 diam.

Fig. 9.—T.S. through upper part of pons Varolii of monkey, showing fine degeneration scattered round the pyramidal bundles on the side of the lesion (left). × 6 diam.

Fig. 10.—The same section. × 60 diam.

Fig. 11.—T.S. Medulla oblongata of monkey through middle of inferior olive, showing fibres passing from the left degenerated pyramid to the formatio reticularis of opposite and same sides. × 6 diam.

Fig. 12.—T.S. Medulla oblongata of monkey through upper part of pyramidal decussation. × 10 diam.

Fig. 13.—T.S. Medulla oblongata of monkey through lower part of pyramidal decussation. Observe homolateral fibres at this level. × 10 diam.

Fig. 14.—T.S. Spinal cord of monkey through sixth cervical segment, showing crossed and direct lateral pyramidal tracts, with a few fibres passing into the base of the posterior horn on the right side.

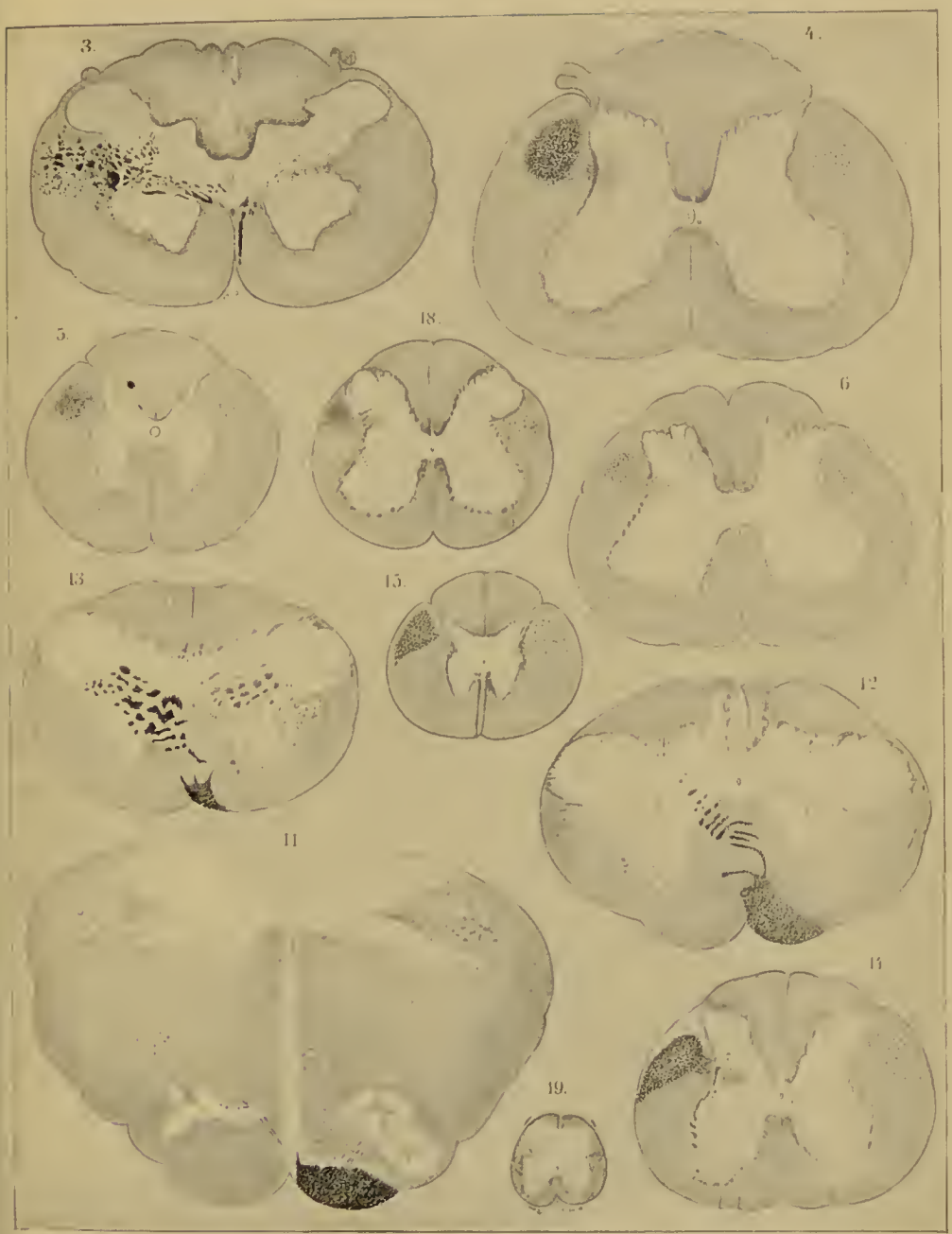
Fig. 15.—T.S. Spinal cord of monkey through fourth dorsal segment, showing homolateral and heterolateral pyramidal fibres.

Fig. 18.—T.S. Spinal cord of monkey through fourth lumbar segment, showing a few fibres from the degenerated crossed pyramidal tract passing towards the grey matter at the base of the posterior horn.

Fig. 19.—T.S. Spinal cord of monkey through fourth sacral segment. The crossed and direct pyramidal tracts are still present at this level.

The pyramidal tract in the cat, dog and monkey.

DR SUTHERLAND SIMPSON.



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